Programme Area: Cross Cutting Projects

Project: UK Energy Systems Model

Title: ESME Modelling Paper

Abstract:

This paper provides an overview of ESME v3.3. The first objective of the paper is to describe, in general terms, what the tool does and what it is used for. The second objective of this paper is to give a more detailed guide to the modelling approach, describing how key features of the problem are represented in the model and noting some of the key assumptions and limitations of the approach. This material is more technical, and will be particularly useful for people with knowledge of other energy models.

Context:

This publication has been produced as part of the work on the ETI’s internationally peer reviewed energy system modelling environment (ESME) - a national energy system design and planning capability that helps to identify key areas for ETI investments. ESME is also used by UK Government to underpin and inform energy policy.

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Modelling Low-Carbon Energy System Designs with the ETI ESME Model

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Abstract

This paper provides an overview of ETI's Energy System Modelling Environment (ESME). The first objective of this paper is to describe, in general terms, what the tool does and what it is used for. This is intended to act as background reference material for anyone who has seen ESME cited in a presentation or report and wishes to find out more about the modelling work behind the headline results. The second objective of this paper is to give a more detailed guide to the modelling approach, describing how key features of the problem are represented in the model and noting some of the key assumptions and limitations of the approach. This material is more technical, and will be particularly useful for people with knowledge of other energy models.

1 Introduction

The Energy Technologies Institute[9] (ETI) is a public-private partnership between global energy and engineering companies BP, Caterpillar, EDF, E.ON, Rolls-Royce and Shell and the UK Government. The ETI was set up in 2007 to accelerate the development of new energy technologies for the UK's transition to a low carbon economy. It brings together engineering projects that accelerate the development of technologies which help the UK address its long term emissions reductions targets as well as delivering nearer term benefits.

A key early initiative for the ETI was to build an energy system model to guide priorities for a portfolio of technology development programmes. ETI's Energy System Modelling Environment (ESME) was originally conceived for ETI's own purposes in identifying and designing investments in technology programmes that provide the greatest strategic added value to its objectives.

Over time ESME has developed into one of the most powerful energy system models for the UK. Although ETI's requirements were initially focused on technology investments, increasingly the use of ESME outputs and insights has expanded into more strategic policy contexts. ESME is in use by ETI's public and private sector members who have increasingly recognised its capacity to generate insights with relevance for wider national decarbonisation policy and strategy. It has been used to support work by the Climate Change Committee (CCC) on carbon budgets and its renewable energy review[3], and by the Department for Energy & Climate Change (DECC), for example, in informing the Carbon Plan[10] and recent heat[6;7] and bioenergy[5] strategies. ETI also makes ESME software licences available to academics for use in research projects, and is considering options for wider commercialisation of the model, database and strategic capability.

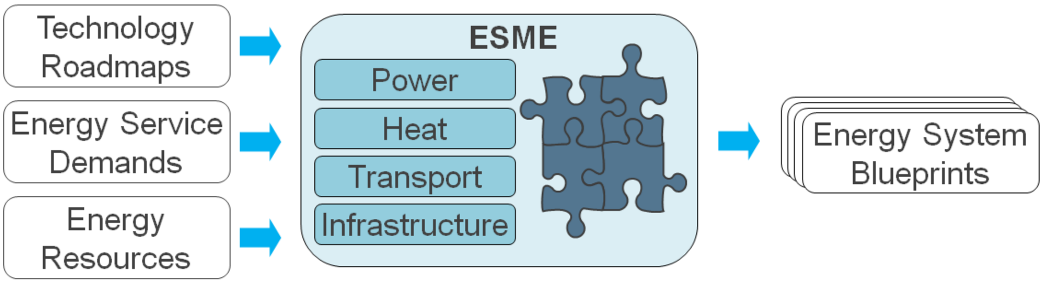

Figure 1: A schematic diagram of the ESME model. Input assumptions for 2010–2050 on energy technologies, demands for energy services and energy resources are combined in a policy-neutral cost optimisation which searches for optimal energy system designs.

1.1 The landscape of energy models

ESME belongs to the class of energy system models which might be termed pathway optimisation models. The central approach is policy-neutral cost optimisation, and a simple schematic is shown in figure 1. With a focus on the long term (2010-2050) pathway, ESME searches for optimal energy system designs which minimise cost whilst meeting stipulated emissions targets and a range of other user-specified constraints. ESME is also a Monte Carlo model which considers the impact of uncertainty in this problem, particularly uncertainty in future energy prices and the future cost and performance of energy technologies. Other pathway optimisation models include Markal[13] and its successor Times[17]. UK Markal[20], a variant of the generic Markal platform configured for the UK, has made several contributions to the climate change policy debate in the UK, see for example Strachan et al.[16], and similar models have also been applied in many other countries. Times models have also been developed for Europe[11] and for the global energy system. The collaborative structure of the ETI provides a distinctive setting for ESME, with the modelling approach and the data being informed by a portfolio of industrial projects and expertise from the ETI members. In terms of model functionality, whilst Markal and Times are pathway optimisation models like ESME there are many important differences in the detailed approach, see §4 for more details. The particular differences to note are the uncertainty analysis undertaken by ESME, which is not part of the core Markal or Times models, and the modelling of energy demand undertaken by Markal & Times which is not part of the core ESME model. However, it is important to note that in addition to the core ESME model* and the core UK Markal model, there are also several variants of both which have been developed for particular projects and which have expanded functionality in particular areas.

Energy modelling is a broad field and there are many other types of models besides the long term optimisation models[18]. Optimisation models are sometimes referred to as 'bottom-up' models because they consider specific technical opportunities and their energy, cost and emission implications. In contrast, 'top-down' models analyse aggregate behaviour using historically-derived economic trends. Top-down models are more suitable for studying economy-wide responses to energy policies and other drivers, and can generate insights into income, GDP, and economic competitiveness, but technological detail and real-world constraints are generally aggregated and hence not modelled in detail. Top-down models include computable general equilibrium (CGE) models such as UKENVI[1] and macro-econometric models such as MDM-E3[2], and have been widely used to study economy-wide effects of energy policies and the transition to a low-carbon economy. In bottom-up models such as ESME the macro-economy is not modelled, but is usually represented via exogenous assumptions which are derived from other work.

Bottom-up models are usually more suitable for studying specific technical opportunities and include optimisation models such as ESME as well as simulation models. The term simulation models

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*At the time of writing the latest version is ESME v3.3

here refers to a diverse category, encompassing all models which simulate the behaviour of a system given a detailed specification of its properties. The simulated system could be anything from a car engine, to a power station, or a transmission network or an energy market. Bottom-up models with a wide scope typically require extensive data sets, which triggers a compromise between a highly disaggregated and detailed model on the one hand, and the constraints of data availability and model complexity on the other. ESME is a long term optimisation model covering the whole energy system, and in consequence it has a very large dataset, but relatively limited detail on the individual technologies within the system when compared to, say, a power station simulation model. Many other models have greater detail focused onto a part of the energy system and these are important sources of information for a whole-system model like ESME. Some of these can be used to ensure that processes are appropriately represented in the wider system model, while others focus on areas not covered by ESME such as the near-term pathway, energy bill impacts, climate change adaptation costs etc.

Detailed models of sectors are particularly important. For example dispatch models are commonly used to model the power sector, looking at the hour-to-hour or minute-to-minute operation of power stations. They are used to study, amongst other things, overall transmission system balancing, or the electricity prices resulting from a given market structure, or strategies for operators to maximise their profit. The number of detailed sector and technology models is legion and a comprehensive review is not possible here. Figure 4 illustrates over 30 sector and technology models developed by ETI alone in its technology projects since 2007, and very many more have been developed by other companies and academics.

The 2050 Calculator developed by DECC[8] is an example of yet another approach. In this tool the user selects their choices for the UK energy system, rather than the model making choices based on an optimisation or a simulation. Based on the user's choices the calculator reports the consequences in terms of energy mix, emissions and indicative cost. While the results are of course limited by the ingenuity of the user, this tool is very powerful for demonstrating the complexity of the energy system and the inter-dependencies between the various technology and policy choices. Indeed it has been developed principally as a tool for engaging the public in the choices surrounding the UK energy system and its decarbonisation.

1.2 The development of ESME

The development of ESME commenced in mid-2008 with a 'proof of concept' design focused on the power sector. ETI subsequently established an advisory group of modelling experts from ETI member companies, DECC, CCC and leading academics, and in 2009 developed a model of the full energy system. A prototyping development style was selected, with external consultants Marakon and Baringa engaged to assist with the design specification, formulation and model construction.

The ESME model has been tested and audited by ETI at various stages during its development, and in December 2010 ETI held a peer review of the ESME model by an international panel of modelling experts from academia and industry. The peer review considered the fitness of the overall modelling approach, as well as incorporating an external technical audit of the code performed by the Energy research Centre of the Netherlands (ECN). The peer review panel concluded that the modelling approach and the tool were sound, and made a number recommendations for further development work which have since been actioned.

Whilst the core model is now relatively stable, work continues to keep the datasets updated in the light of external developments, and in particular in response to insights from ETI's other projects and technology analyses. In 2013 a prototype EU ESME model was built, to demonstrate application of the same approach to model the energy system of Europe. Ongoing validation of ESME continues via ETI's modelling advisory group, which meets regularly to discuss modelling issues and to review the ESME model outputs.

2 ESME Scope & Approach

In this section we will give an overview of the approach and key features of ESME. A more detailed account of the model is given in §4 below.

ESME is a least-cost optimisation model of the whole UK energy system which ETI has developed to perform energy system analysis which informs ETI's technology strategy. The ESME optimisation finds the least-cost energy system designs which meet stipulated sustainability and security targets, taking account of technology operation, peaks in energy demand and UK geography. ESME is a Monte Carlo model which considers the uncertainty in this problem, particularly uncertainty in future energy prices and the future cost and performance of energy technologies. This functionality allows the user to explore system-level responses to user-specified uncertainty in the future values of key assumptions.

The central approach taken in ESME is a policy-neutral cost optimisation. The aim of the model is to examine underlying cost and engineering challenges of designing energy systems, and therefore taxes, subsidies and other policies which affect the price of technologies or fuels are absent. The idea is that ESME (and similar policy-neutral tools) can give insights into what might be desirable future energy systems designs. This can then be the starting point for analysing what policies, markets and incentives could be aligned to deliver energy systems in future.

The 'whole system' scope includes all the major flows of energy: electricity generation, fuel production, heating and energy use in buildings, energy use in industry, and transportation of people and freight. Various technology choices are available in each of these sectors, such as alternative power stations, vehicle types or heater types. ESME performs a high-level cost optimisation that analyses different combinations of technologies in each sector and selects the combinations which together minimise the total cost while meeting specified targets and constraints.

2.1 Cost optimisation

The cost optimisation at the heart of the approach taken in ESME is structured to reflect a number of key design criteria:

- Focus on the long term transition pathway. ESME can consider pathways from 2010–2050, driven by long term trends in energy technologies and in the demand for energy services. Different long term views of the UK are explored via 3 cases with contrasting future trends for UK population and the strength & makeup of the UK economy.

- Engineering orientation. The key outputs are energy system designs which specify the capacity and pattern of operation of technologies in future energy systems. Technologies cover power, buildings, transport, industry and the associated infrastructure which connects them. The resolution is high-level (around 250 technologies are considered) but includes sufficient engineering detail to distinguish between the key technology choices.

- Treatment of uncertainty. Monte Carlo simulation is used to reflect uncertainty in key assumptions including energy resources, fuel prices and technology costs. The Monte-Carlo functionality enables ESME to undertake hundreds or thousands of runs based on different combinations of parameters sampled from user-specified ranges.

- Temporal factors. The UK energy system design is strongly influenced by peak levels of demand, e.g. peak electricity demand and peak space heating demand. ESME accounts for seasonal and diurnal variations in energy demands, and explores the trade-offs between various ways to manage peak demand (e.g. supply, storage, efficiency and demand-side measures).

- Spatial factors. Geographic factors are increasingly significant as renewable resources (e.g. offshore wind) are exploited which require significant new infrastructure. ESME represents the UK energy system at a regional level via 12 onshore and 12 offshore regions. Energy demands, natural resources, technology choices and infrastructure are all represented at this regional level.

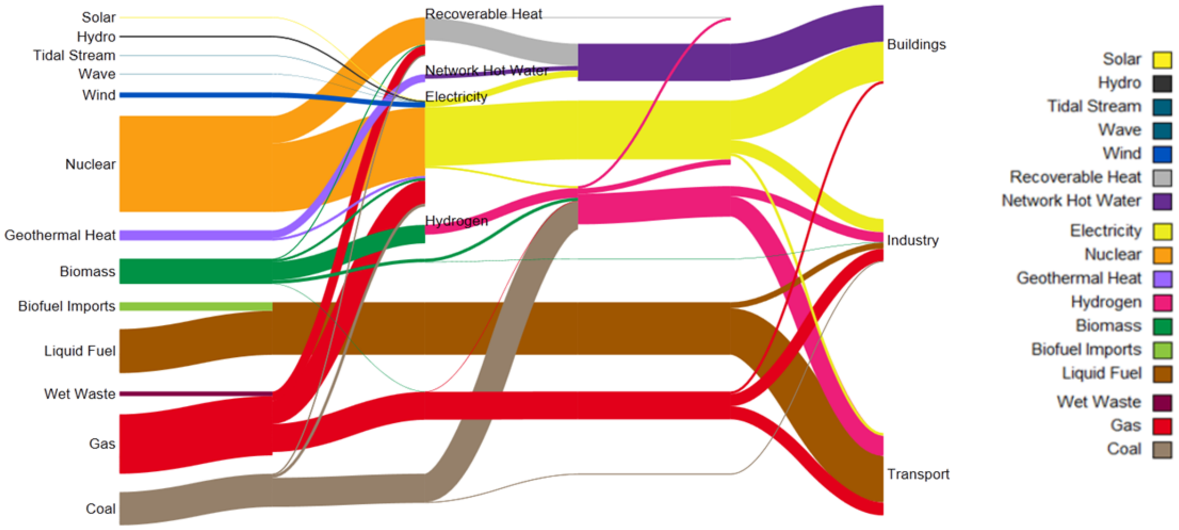

Figure 2: An example schematic of the energy flows, from left to right, in an ESME energy system design for 2050.

- Cost minimisation. The optimisation selects the optimal value of all decision variables such that the total discounted energy system cost is minimised. Cost is defined as the annualised investment, operations and maintenance costs for the technologies deployed, plus aggregate fuel costs and energy import costs.

Decision variables are the quantities which are determined during the cost optimisation performed by ESME. The key decision variables are:

- The capacity of energy technologies. I.e. which technologies to deploy, how much to deploy, where and when.
- The level of retrofits to apply to pre-existing technologies. Retrofits include adding Carbon Capture & Storage (CCS) to a power station, or improving the thermal efficiency of an existing house.
- The operating pattern for each energy technology. For example, the daily pattern of electricity generated by each power station type and the daily pattern of heat production by domestic heaters.
- The transmission capacity and pattern of energy flows between UK regions.
- The capacity and operating pattern of energy storage technologies.
- The quantity of fuels and energy resources used by energy technologies, e.g. natural gas imports and offshore wind resource.

Taken together, the values of the decision variables determined during the optimisation constitute an ‘energy system design’. Examples of the information contained in an ESME energy system design are given in Figures 2 & 3. Figure 2 shows a Sankey diagram, a single chart which summarises from left to right all the energy flows from primary resources through to energy consumption by end consumers. Figure 3 shows how the optimisation process makes choices on the quantity and type of technologies to deploy, figure 3a showing a national summary of choices for space heating and figure 3b showing a regional view of choices for power generation capacities in 2050.

The cost optimisation in ESME is subject to a number of constraints which may apply differently in different locations within the UK and at different times. The key constraints are:

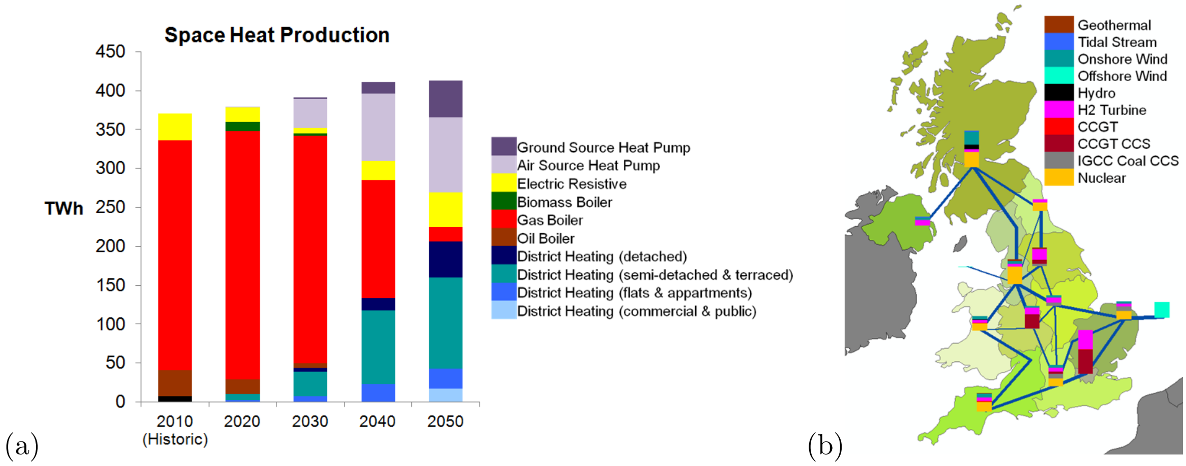

Figure 3: Examples of the information comprising an ESME energy system design. (a) Technology selections , in this case for the provision of heat. (b) Regional technology selections, in this case power generation.

- All energy service demands must be satisfied.
- Total CO_2 emissions must meet the user-defined targets in each year.
- The consumption of energy resources must respect the user-defined limits.
- The deployment of technologies must respect user-defined limits on the rate of deployment and any limits on the maximum permitted deployment.
- Product balances: the production and consumption of all energy vectors and products should balance, allowing for transmission, storage and losses.
- The energy system must satisfy various security of supply constraints. The first of these requires sufficient capacity to meet the estimated *peak* demands for both electricity and heat. Also there must be enough capacity so that electricity demands could be met during a multi-day period of no wind, and enough ‘flexible’ electricity generation capacity to meet varying demand.
- If specified, near-term minimum levels of deployment must be met.
- User-specified links between technologies must be respected. E.g. the number of ground source heat pumps cannot exceed the number of houses suitable for this type of heater.
- UK renewable energy targets for 2020 are modelled, and the user can choose whether these must be met.

Note that the emissions constraint in ESME is specifically a constraint on CO_2 emissions. The expected pathway of emissions from other greenhouse gases are taken into account when specifying the maximum level of CO_2 emissions to be permitted, but other greenhouse gases are not tracked in ESME.

2.2 Required data sets

The data sets required to run the ESME model fall into three broad categories. The first is a set of assumptions on demand levels for energy services. There are 28 energy services, spread across industry, transport and buildings; for each of these an annual demand level must be specified from 2010–2050 in each of the 12 onshore regions of the UK. These are long term projections based on future trends for UK population and the strength and makeup of the UK economy. ETI has 3 alternative cases of

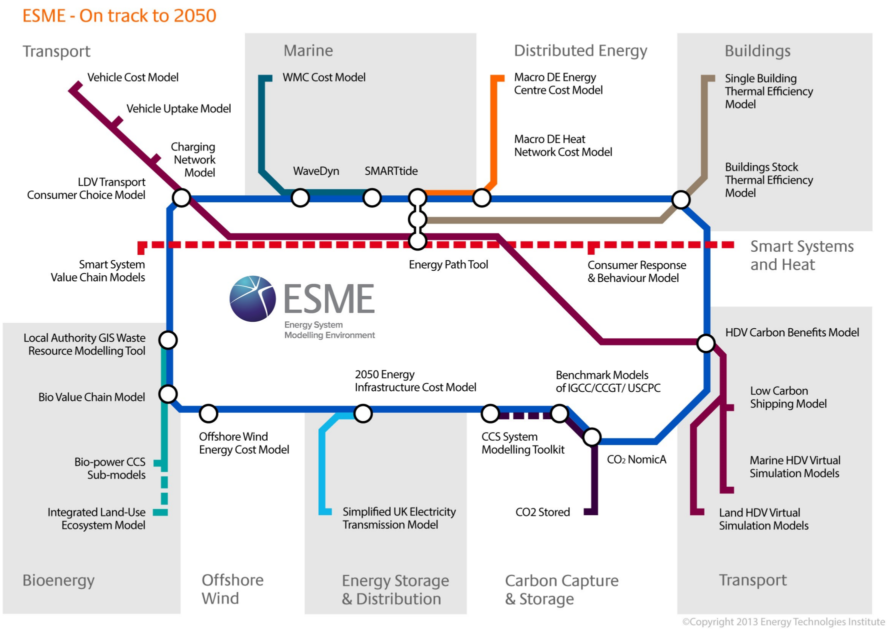

Figure 4: A schematic map of ETI projects and models which interact with ESME. Each 'station' represents an ETI project or sector model which provides data to ESME, or to which ESME provides data on the broader energy system.

which one is based on the central projections of the UK Government and two alternatives, each with an associated narrative.

The next category of required data is technology roadmaps. These are a database of assumptions on the cost and performance of all the technologies included in the model through to 2050. ETI runs ESME with a database of around 250 energy technologies. For each technology there are a few required parameters such as technical lifetime, length of construction period and the list of UK regions in which deployment is feasible. In addition there are many optional parameters which can be specified, of which not all are relevant to every technology. Cost parameters include: capital cost, fixed costs & variable costs. Performance parameters include efficiency, maximum load factors, CO_2 capture rates, security of supply parameters etc.

Finally, there is also a set of assumptions on energy resources. These include technical parameters such as the energy content and carbon content of energy carriers, and assessments of the indigenous UK resources of renewable energy such as wind, solar and biomass. Also required are assumptions on the cost to 2050 of globally-traded fuels such as fossil fuels, uranium and imported bioenergy.

ETI has a proprietary dataset which it uses to drive the ESME model constructed from original sources which are either external publications or proprietary ETI sources. The original source data underlying the energy service demands are all published government statistics for example, and most of the energy resource data is also based on published reports. The technology data however relies on a significant amount of proprietary data, most of which is derived from other ETI projects. For example, ETI has funded projects which look at the detailed design of future offshore wind turbines as part its wider offshore wind programme. The latest results from these projects are incorporated into the technology roadmap for offshore wind in ESME, and similarly across other technology areas. Likewise, ETI's more detailed sector models, e.g. on bioenergy and heat, provide data which is used in ESME. In fact information flows in both directions, as ESME can provide information on the broader energy system which is used to run detailed sector or technology models, see Figure 4.

2.3 How ETI uses ESME

ETI uses ESME to explore the different roles which technologies could play in future energy systems. The ETI's goal is to de-risk high impact technologies, and analysis using ESME ultimately helps to inform the key areas for strategic investment. Some examples of the types of questions which ESME analysis can inform are given below:

- What might be 'no regret' technology choices and pathways to 2050?
- What is the total system cost of meeting the energy targets?
- What are the opportunity costs of individual technologies?
- What are the key constraints e.g. resources, supply constraints?
- How might accelerating the development of a technology impact the solution?
- How might uncertainty in resource prices and availability influence system design choices?
- Where should new generating capacity optimally be located?
- How might policies and consumer choices influence technology development?

ESME can provide a direct answer to some of these questions, while for others it can only give a contribution which must be combined with information from other sources.

There are clear ways in which 'optimised' energy system designs produced by ESME have appealing value, however to answer questions such as those above it is important to place model results in a suitable context. The results of any model are strongly dependent on how the model is run and how the data is used, and all models have limitations which need to be understood. In fact, it is reasonable to ask ourselves what can energy system modelling actually tell us that is relevant to real world decision making? We should indeed be cautious about the limits of our present day knowledge, let alone the ability of a model to accurately represent such a complex system. Modelling can only simplify and approximate real world complexities, political constraints, and imperfect knowledge, so its use in informing investment choices must be tempered with caution and judgment. Nevertheless, many of the investments needed in the energy sector are in long-lived assets, so the need to take a view far into the future is unavoidable. While 'picking winners' over such a timescale is unrealistic, modelling the long term pathway does give some opportunity to identify 'contenders', i.e. technologies which could play an important role in future energy systems. Modelling can form part of a process of filtering contenders for further support before, ultimately, they will sink or swim in a competitive market.

So, care is required to perform a thorough ESME analysis from which robust conclusions can be drawn. Comprehensive sensitivity analysis lies at the heart of this, i.e. testing how the model results change in response to a range of different assumptions, in order to build a broad understanding of the model results and to put them into context. Ideally one hopes to identify 'no regret' technology pathways which are an important part of the future energy system design in any scenario. The Monte-Carlo uncertainty analysis embedded in the ESME approach is directly relevant to this. To reflect the inherent uncertainty in estimates of future technology costs and future fuel costs, for example, ESME allows the user to define ranges and probability distributions for the future values of these parameters. The user can also, optionally, specify correlations between any of the uncertain parameters (e.g. costs of gas CCS and coal CCS power stations). ESME can generate many hundreds or thousands of energy system designs in a single Monte-Carlo model run, each corresponding to the least-cost energy system in a different eventuality. The combined results can then be used to assess the technology capacity levels seen in the optimised energy systems under the assumed uncertainties. The distributions of other outputs, such as the total energy system costs or derived quantities such as electricity grid carbon intensity can be similarly studied. When interpreting the results it is important to note that for each individual case in a Monte Carlo run, the optimisation is performed with knowledge of the costs and prices in all years, so decisions in the early years effectively benefit from perfect foresight. With careful interpretation the results can suggest strategies for managing risk and timing of decisions, but that must be inferred off-model. Ultimately, the Monte-Carlo functionality effectively automates a large volume of sensitivity analysis.

So, by using the Monte Carlo functionality of ESME to look at a range of outcomes, a technology might appear to be a 'no hoper', or perhaps a 'marginal contender' or even a 'no regret' option in the face of the quantified uncertainties. However this is only one aspect and there are others to consider. As an alternative to asking how much and how often is a technology seen in the ESME results, one can also ask what is the *importance* of that technology within the system design. ETI often uses an 'opportunity cost' metric to think about this question. The opportunity cost of technology X is defined to be the difference in cost between the energy system designs from two different ESME runs:

(i). An ESME run using standard assumptions

(ii). An ESME run using standard assumptions, except that technology X cannot be deployed

Because the energy system cost is minimised in both runs, then it follows that the system cost of (ii) is greater than or equal to the system cost of (i). The opportunity cost of a technology is a measure of both the scale of deployment and the degree to which the technology can be 'substituted' in the energy system design. If a technology is found to be widely deployed in the ESME energy system but has a low opportunity cost this implies that it can be readily substituted at little additional cost. A detailed inspection of the two runs is required to understand the reason for a low opportunity cost arising, but it could indicate that the technology has one or more close competitors and that, in the long run, it is not very significant which of them succeeds. In contrast a high opportunity cost indicates that a technology is of high importance because it is very expensive to substitute. ETI regularly performs an opportunity cost analysis in this way, which entails running many different 'no technology X' sensitivity cases in ESME.

Another aspect of the ESME analysis performed by ETI is to look at uncertainties which are not quantified directly in the Monte Carlo model. These include broader uncertainties such as 'What if the demands on the UK energy system are significantly different?', or 'What if a novel technology proves infeasible?'. This latter case could arise for various reasons, e.g. technical or political, and is quite different from the question 'what if the technology is more expensive than anticipated?' covered by the Monte Carlo analysis. This issue is most obviously relevant for technology options which are reliant on uncertain factors outside the model scope, e.g. public acceptance or regulatory issues. The 'no technology X' sensitivity cases run as part of the opportunity cost analysis described above can be applied here. To address the question 'What if the demands on the UK energy system are significantly different?', ETI has developed 3 alternative scenarios for the levels of future energy service demands which are based on three alternative socio-economic pathways for the UK. These are used to explore the impact on the energy system of variations in the total demand for energy services as well as variations in the type of demand, e.g. more commuting and office work versus more home working.

Yet another approach to the broad sensitivity analysis possible with ESME is to look at variations in the results under different CO_2 targets. While the statutory greenhouse gas targets for the UK are fixed by law, there is naturally some uncertainty over the level of emissions reduction which will prove possible in the non-CO_2 sectors and in the extent to which international emissions trading will be sanctioned. Both of these are externalities beyond the scope of the ESME model, but which impact on the budget allowed for the CO_2 emissions which are within the model scope. It is therefore an instructive thought experiment to look at variations in the CO_2 target imposed in ESME, and to see what combinations of technologies are optimal in different cases. This gives further contextual information on the role which different technologies play in the ESME results, and their importance in the bigger picture.

In total then, ETI typically performs very many different model runs and uses these to test the results and to explore the key trade-offs and uncertainties, gradually building up a picture of the role played by individual technologies. A good example of this is given by Carbon Capture & Storage[4] (CCS). ESME points clearly to CCS as a key contender technology for the UK energy system. At this stage CCS has not been deployed at commercial scale within the UK, but ESME modelling is robust in pointing to a high potential system-wide value for CCS in the long term. In our ESME modelling CCS delivers major benefits, is robust to alternative scenarios and is important in determining the overall architecture of the national energy system. The scale and robustness of this potential value reflects the specific interactions of CCS across the energy system: because there is no straightforward substitute for CCS, in a 'no CCS' case the system design is very different and has very different, much higher costs.

The conclusion that CCS is a valuable contender technology raises further questions, and some of these are amenable to further study with ESME. For example, one might ask about the impact of unforeseen costs or performance issues, or breakthroughs in competing technologies. The idea would be to understand what would need to happen to displace CCS from a future system, perhaps by modelling hypothetical breakthrough technologies or assessing how wrong forecasts of CCS cost and performance would need to be to erase its future value.

2.4 How other organisations use ESME

As well as in-house use by ETI analysts, ESME is in use by ETI's public and private sector members. BP, Caterpillar, E.ON, Rolls-Royce and Shell have all used ESME internally to varying degrees. Applications range from testing simple scenarios with different assumptions to the standard ETI set, through to building ESME models of other countries.

Its capacity to generate insights with relevance for wider national decarbonisation policy and strategy has also seen ESME used by policy makers. It has been used to support work by the Committee on Climate Change (CCC) on carbon budgets and its renewable energy review[3], and by the Department for Energy & Climate Change (DECC) in informing the Carbon Plan[10] and recent heat[6;7] and bioenergy[5] strategies.

Policy makers look at a wide variety of issues and, as noted in §1.1, a long term optimisation model is not suitable for every question. For a question such as "what is the impact of policy X in the 2020s?" then models with a shorter time horizon would be better suited because they will have more granularity of detail to model policy X and other existing or planned policies. For example, the DECC Energy Model is good at modelling policies to 2030, whereas models with longer time horizons do not model individual policies in sufficient detail to provide robust short term projections, or to inform the detailed design of individual policies. A pathway model such as ESME is more relevant to investigate technically feasible pathways towards long run emissions reduction targets, and to inform decisions on long run policy objectives. So, whilst ESME was originally designed for analysing energy technology choices rather than for policy analysis, it can be useful to policy makers. It can be used to inform market and policy design, increase understanding of pathways (including the impacts of real world constraints and inertia in deploying technology), and identify key 'contender' technologies with particular system-wide value.

ETI also makes ESME software licences available to academics for use in research projects, an early example of this is the energy-economics modelling group at University College London. The standard licence gives access to the full model, source code and ETI datasets which can be used or modified for the purposes of a named research project. Journal publications of results and analysis are encouraged. Academic applications of ESME include a novel Bayesian network approach to uncertainty[21] and modification of ESME to include demand modelling via elasticities[15]. Planned future work will also see ESME used in the UKERC 'Energy Strategy Under Uncertainty' project[19].

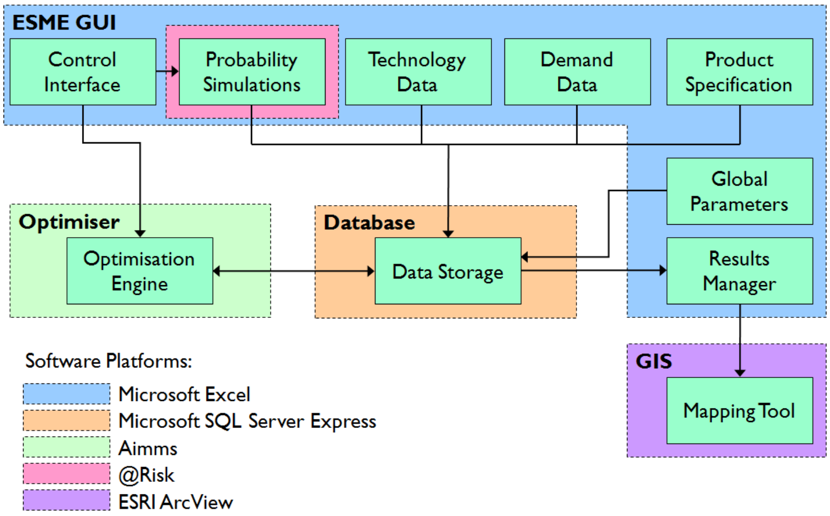

Figure 5: The software architecture of the ESME model.

3 ESME Architecture

3.1 Software architecture

The ESME model software is comprised of a number of interlinked components, as shown in Figure 5.

- The ESME Graphical User Interface (GUI) is based in the Microsoft Excel$^{\mathrm{TM}}$ platform. The GUI allows the user to enter and modify model input data, and to run ESME and analyse the results without needing to interact directly with any of the other model components.

- The ESME database is based in the Microsoft SQL Server Express$^{\mathrm{TM}}$ environment. The database stores all of the model input data and all results data. The database also facilitates the exchange of this data between the GUI and the optimiser via a collection of predefined queries and stored procedures.

- Palisade @RISK$^{\mathrm{TM}}$ is used as for probability simulations. The @RISK add-in to Microsoft Excel is incorporated into the ESME GUI to provide the probabilistic simulation functionality.

- The ESME optimiser is based on the Aimms$^{\mathrm{TM}}$ optimisation platform. Aimms provides the framework for the Linear Program (LP) optimisation model. The optimisation is populated with input data from the ESME Database and controlled by the ESME GUI. A standard Aimms licence includes an open-source solver for performing the optimisation, and other commercial solvers are also available. CPLEX$^{\mathrm{TM}}$ is the recommended solver for the ESME model.

- GIS (Geographical Information System): ESRI ArcView software provides the functionality to generate geographical plots of selected model results. The ESME GUI can export specific results as data files in a format suitable for importing into ArcView

3.2 Data-driven flexibility

An important feature of the ESME optimisation model is that it is constructed to be a *data-driven* model. Data-driven programming is a programming paradigm in which the code specifies generic processes to be applied to incoming data, rather than a sequence of procedures to be executed. A data-driven model is naturally amenable to customisation and modification, which facilitates the various types of sensitivity test cases described in §2.3. It also means that the model is relatively easy to adapt, e.g. to model energy systems in alternative countries or regions.

The ESME optimiser receives from the database data which a user has entered via the GUI, and this data is used to construct a mathematical optimisation which can then be passed to a solver. For example, the list of available technologies is determined by the user in the GUI, as are the lists of: energy vectors, energy services and regions of the UK being modelled. The GUI ensures that user-entered data is appropriately structured, but otherwise the user can control the size and complexity of the optimisation.

Though avoided where possible, some special cases are necessary and are hard coded in the model. For example, electricity and heat are treated as special products because they have security of supply constraints to be met (see §2.1). These special cases are kept to a minimum, and in most respects all products, regions, technologies etc. are treated equally.

4 ESME Modelling Approach

The aim of this section is to give a more detailed account of the ESME model than the descriptions in §2 above. As such, this section contains more technical details, and is aimed at readers with some experience of energy modelling.

4.1 Model Ontology

As described in §3.2 the ESME model is data driven. Users enter data via the GUI into a structured database, and the data ultimately controls the structure and resolution of the optimisation which is performed. The key entities in the ESME database and optimisation are defined below.

Products

A generic term for all quantities which are potential inputs or outputs of a technology in the model. The products comprise:

- Energy resources. These are products which are available from outside the energy system (either at a cost or free of charge) e.g. coal, gas, nuclear fuel, wind resource, solar resource, etc.

- End use services. These products represent services which the energy system must provide. An important distinction is made between the end use services and the technologies which supply them: the technology is unspecified *a priori*, to be determined by the optimisation process, but an end use service represents a fundamental demand which must be met. The demand level for each one is set by exogenous assumptions (see §2.2 & §4.4). For each end use service the model must include one or more technologies capable of producing it.

  Examples include: passenger km of car transport (produced by various car technologies), passenger km of aviation transport (produced by aviation technologies), tonne km of road freight (produced by various HGV technologies), detached homes (produced by various dwelling technologies), industry sector output (produced by industry sector technologies) etc.

- Energy carriers. These are products which can be produced and consumed within the energy system e.g. electricity, hydrogen, space heat. Space heat, for example, can be produced by a number of different heater technologies (gas boilers, heat pumps ...) and is a required input for each dwelling. Different dwellings are available, at varying cost and varying thermal performance. The selection of heater types and dwelling types is made by the optimisation, but in any combination a quantity of space heat will be produced by the heater and consumed by the dwelling.

- Emissions. This is principally CO_2, but could be any product for which a net production is to be expected (i.e. total production exceeding total consumption). A distinction is drawn with energy carriers because, whilst net production of an energy carrier is permitted, it is *not* expected and might be an indication of incorrect model behaviour: it is usually cheaper to produce less hydrogen, say, than to produce an excess.

- Emission carriers. 'captured CO_2' is the only such product in the current version of ESME. It is a product that cannot be released: total production must exactly match total consumption.

Technologies

A technology is any process which converts one or more product into one or more product. This broad definition includes power stations, fuel conversion, vehicles, heaters, cookers, buildings, industry sectors etc. Technologies may be operated in a number of different modes with different inputs, outputs and efficiency. Technologies have various cost and performance attributes – see §4.6 below.

Storage technologies

A storage technology is a process that is capable of storing a product from one time to another. Storage technologies have various cost and efficiency attributes – see §4.8 below. Depending on the temporal representation of the product in question, the storage could be either diurnal (i.e. storage between two times in a day) or seasonal (i.e. storage between summer and winter).

Transmission technologies

A transmission technology is one which moves a product from one region to another. Transmission has cost and loss factor attributes – see §4.7 below.

Retrofit technologies

A retrofit technology has the effect of converting one unit of a pre-existing technology (the parent) into one unit of a second technology (the child). Examples include CCS power station retrofit, which converts 1GW of the 'CCGT' technology to 1GW of the 'CCGT with CCS' technology, and insulation retrofits which improve thermal efficiency by converting 1 dwelling with a given thermal efficiency rating to 1 dwelling with a higher rating.

4.2 Time

There are two distinct aspects to the representation of time in ESME, the first aspect being representation of the long term pathway 2010 – 2050. The combinations of technologies which can meet the UK's carbon targets in 2050 is one question and an equally important question is how can the energy system transition from today to 2050. The cost and feasibility of the transition is material and important to consider: transition could potentially take decades in some sectors and raises questions about infrastructure 'lock in'. Using a pathway model to build understanding of the uncertainties and trade-offs in the transition allows some conclusions to be drawn about risk & decision timing over the pathway 2010 – 2050.

The second aspect of time representation in ESME is shorter timescale (i.e. within-year) variations in the supply and demand of energy. Annual totals for the energy flows (e.g. Figure 2) give only a partial picture. For some energy vectors a year comprises a mixture of periods with very high levels of demand and others with very low demand. The energy system design is strongly influenced by the peak demand for energy, and particularly space heating. Variations in demand both during the year and during the day have an impact on technology choices: competing technologies can have different levels of responsiveness and a different balance of capital, fixed and variable costs. Hence the modelling approach must account for both seasonal and within-day energy requirements to be able to explore the trade-offs between options to manage peak demands for energy: peak supply capacity, energy storage, energy efficiency and demand management interventions.

(a)

Seasonal timeslice	Definition
Summer	April-September
Winter	October-March

(b)

Diurnal timeslice	Definition
Summer Morning	Summer, 6am - 10am
Summer Mid-Day	Summer, 10am - 4pm
Summer Early Evening	Summer, 4pm - 7pm
Summer Late Evening	Summer, 7pm - 11pm
Summer Overnight	Summer, 11pm - 6am
Winter Morning	Winter, 6am - 10am
Winter Mid-Day	Winter, 10am - 4pm
Winter Early Evening	Winter, 4pm - 7pm
Winter Late Evening	Winter, 7pm - 11pm
Winter Overnight	Winter, 11pm - 6am

Table 1: The standard seasonal timeslices (a) and diurnal timeslices (b) used in ESME.

Pathway Representation

The base year in the ESME model is 2010. Starting conditions such as levels of existing technology stock can be specified but an optimisation cannot be performed for 2010. The set

$$\mathbb{B} = \{2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050\} \tag{1}$$

defines all the years represented in the model, with the user free to select any combination to include in the pathway optimisation.

The subset of years selected for the optimisation is denoted $\mathbb{T}$. Each selected year $t \in \mathbb{T}$ is treated as a single specific year in which all constraints on the energy system must be met (energy service demands, emissions targets etc., see §2.1). This means that for all the years in the set $\mathbb{T}$ a complete energy system design is determined and the annualised total cost of the energy system can be evaluated. The objective function for the optimisation is to minimise total cost throughout the modelled pathway, so the energy system costs for all years $t \in \mathbb{T}$ are combined into a single cost metric, see §4.11 for details.

The full set of years $\mathbb{B}$ is used in the ESME optimisation to define the permissible years in which new deployment of technologies is possible. The full set of 'buildyears' $\mathbb{B}$ is used so that the deployment constraints during the pathway, particularly maximum build rates, are well represented. Each buildyear $b \in \mathbb{B}$ represents a five year period for deployment: deployment tagged to $b = 2030$, for example, refers to deployment during the five year period from 1^{st} Jan. 2025 to 31^{st} Dec. 2029.

The buildyears approach also has the effect of capturing technology vintages. Technology data typically include assumptions that technologies will improve over time, with costs decreasing and/or efficiencies increasing, to represent future learning curves. If, say 1 GW of CCGT power station is deployed in $b = 2030$, then that power station will have the cost and efficiency parameters corresponding to $b = 2030$ for its entire technical lifetime. In any year $t \in \mathbb{T}$ included in the optimisation, there will typically be many power stations of different vintages, and different decisions are made for how to operate each vintage.

Timeslicing

ESME uses timeslices, subdivisions of the year given in Table 1, to represent within-year variations of energy supply and demand. Each year t included in the optimisation is represented as a collection of these timeslices, which allows differentiation between levels of energy supply and demand on typical summer mornings, summer evenings etc. Timeslices are a significant improvement on annual averages, but it is important to note that they do not constitute a sequential & chronological representation of a year – something which is much more computationally demanding and which is generally only attempted in simulation models with a narrower scope, e.g. electricity dispatch models. In order to keep the system-wide optimisation computationally feasible and with reasonable solution times the simpler timeslice representation is used in ESME.

The timeslice definitions given in Table 1 are chosen to reflect the major variations in UK electricity demand, which peaks in the evening, and UK heat demand, which has daily peaks in both the morning and evening as well as having significant seasonal variation. Resolution could of course be improved by increasing the number of timeslices further. Including more seasons or distinguishing between weekdays and weekends would both be attractive options, however increasing the number of timeslices will have a strong impact on the problem size and hence solution time. The total problem size of the optimisation, as measured by the total number of decision variables and constraints, is roughly proportional to the number of timeslices, see §4.11.

Each product is given a timeslicing category: non-timesliced (NTS) products are resolved at an annual level only, seasonally timesliced (STS) products are resolved at a seasonal resolution only and fully timesliced (TS) products are resolved at all 10 timeslices within each year. This is done to keep the problem size manageable, with products such as electricity and heat categorised as TS in order to capture important temporal variations, but products such as coal and nuclear fuel are NTS.

4.2.1 Time: related decision variables

- All decision variables related to deployment, e.g. capacity of new technology deployed, capacity of retrofit technology applied etc. are indexed over buildyears b.
- All decision variables related to technology operation are indexed over optimised years t and buildyears b (to capture technology vintages).
- All decision variables related to products, i.e. resources consumed and emissions released, are indexed over optimised years t.

4.2.2 Time: related constraints

- All product balances are applied for each optimised year t. For NTS products a single annual balance is applied for each t, for STS a balance is applied for each season and each t, for TS products a balance is applied for each timeslice and each t.
- The energy service demands must be met for all optimised years t.
- All constraints on deployment of technologies, e.g. maximum build rates, are applied for the buildyears b.
- All security of supply constraints are applied for each optimised year t.
- The CO_2 emissions constraint restricts the maximum emissions during each year t for which the user has specified a maximum.
- A RED constraint ensures that renewables targets are met in each year t for which a target is specified. The accounting method of the Renewable Energy Directive is used, under which the UK has a target of 15% renewable energy in 2020.

4.3 Space

ESME represents the UK energy system at a regional level via the 24 regions shown in Table 2. Of these, 12 are onshore regions in which energy service demands are specified. There are 9 offshore regions with wind and marine energy resources and 3 offshore regions in which geological storage of CO_2 is modelled. All aspects of the energy system are specified at a regional level in ESME, so in principle there is little distinction between the onshore & offshore nodes. The difference is really a reflection of the user-defined assumptions of which technologies are permitted in which region.

Onshore regions	Offshore resource regions	Offshore CO_2 storage regions
East	Channel Islands	Central North Sea
East Midlands	Dogger Bank	East Irish Sea
London	East Scotland	Southern North Sea
North East	Hebrides	
North West	Irish Sea	
Northern Ireland	Lundy	
Scotland	Norfolk	
South East	Pentland	
South West	Shetlands	
Wales		
West Midlands		
Yorkshire & Humber		

Table 2: The UK regions used in ESME.

Geographic factors become increasingly significant as remote renewable resources are exploited which require significant new infrastructure (e.g. transmission infrastructure for offshore wind). The approach taken in ESME attempts to capture the need for new infrastructure in order to include its cost in the overall cost of the energy system. Similarly, technologies which rely on particular local geography, such as geothermal heat or pumped hydro energy storage, are not available in all regions of the UK and may drive different choices in different regions. As well as capturing the availability of technology choices across the regions, the ESME approach also allows for the attributes of technologies to be specified per region. Examples include the loadfactors of wind & solar power and the energy required to heat a given type of house. The cost of a technology can also vary regionally, for example the cost of installing a district heat network, which is strongly related to the density of the local buildings and heat demand.

4.3.1 Space: related decision variables

- Almost all decision variables are indexed over regions i. Technology deployment, technology operation, production & consumption of products are all specified at a regional level.
- Decisions variables related to transmission are defined per pair of adjoining regions (i, j), see §4.7

4.3.2 Space: related constraints

- Almost all constraints are applied over each region i. Two exceptions are the CO_2 emissions constraint and the RED renewables constraint which are both applied at a whole system level (i.e. national UK level).
- Energy resource limits are notable regionally varying constraints.
- The energy service demands must be met in each region i. The regional variation in the demands (provided as input data) reflects regional diversity in terms of commercial versus industrial activity, transportation mode, density of population and building stock.
- All product balances are applied for each region i.

4.4 Demand

Demand is represented in ESME via 28 energy services, see Table 3, for which the levels of demand are exogenous inputs specified by the model user. For each energy service an annual demand level must be specified from 2010–2050 in each of the 12 onshore regions of the UK. Generally, the optimisation

Sector	Energy Service Demand	Unit
Domestic	High Density Dwellings	million dwellings
Domestic	Mid Density Dwellings	million dwellings
Domestic	Low Density Dwellings	million dwellings
Domestic	Appliances	TWh
Domestic	Cooking	TWh
Domestic	Air conditioning	TWh
Services	Commercial Floorspace	million sq metres
Services	Public Floorspace	million sq metres
Transport	Aviation Domestic Passenger	billion passenger km
Transport	Aviation International Passenger	billion passenger km
Transport	Rail Passenger Electric	billion passenger km
Transport	Rail Passenger Diesel	billion passenger km
Transport	Rail Freight Diesel	billion tonne km
Transport	Road Passenger Car (A/B Segment)	billion passenger km
Transport	Road Passenger Car (C/D Segment)	billion passenger km
Transport	Road Passenger Bus	billion passenger km
Transport	Road Freight HGV	billion tonne km
Transport	Road Freight LGV	billion tonne km
Transport	Maritime International Freight	billion tonne km
Transport	Maritime Domestic Freight	billion tonne km
Industry	Iron, Steel and Non-Ferrous Metals	Energy demand relative to 2010
Industry	Chemicals	Energy demand relative to 2010
Industry	Metal Products	Energy demand relative to 2010
Industry	Food, Drinks and Tobacco	Energy demand relative to 2010
Industry	Paper, Printing and Publishing	Energy demand relative to 2010
Industry	Other Industry	Energy demand relative to 2010
Industry	Refined Petroleum Products	Energy demand relative to 2010
Industry	Agriculture	Energy demand relative to 2010

Table 3: Energy services which have specified demands in ESME.

will include a choice of technologies which can satisfy each energy service demand, and in turn the technologies consume resources or energy vectors. In contrast to the energy service demands, these demands for resources and energy vectors are endogenous within the model: they are determined by the technology choices as part of the cost optimisation.

Note that all energy service products are NTS, so only an annual balance constraint is applied to ensure that supply meets demand. In all cases, the within-year variations in supply and demand for energy vectors is driven in ESME by the attributes of *technologies*. For example, each house technology which can meet the demand for 'dwellings' in the domestic sector has requirements for space heating, water heating and lighting. These requirements all vary by timeslice and hence drive the product balances of the 3 corresponding TS energy vectors which are resolved at the full timeslice resolution.

ETI has 3 alternative cases for future energy service demands. Each demand case represents a different view of future population and economic growth patterns, resulting in different projections of energy service demand in terms of total demand, mix of energy services, regional split and pathways to 2050. These 3 cases are used to explore alternative energy systems, as described in §2.3, as part of the broad sensitivity testing which looks at energy system design in response to uncertainties. Of the 3 cases one is a reference case, aligned as closely as possible to the UK Government's latest economic growth and demand forecasts and developed through extensive discussions with the relevant Government departments; it can be seen as a high demand case, representing a return to 'business as usual' after a decade of slow economic growth post the 2008 crisis. The two alternative cases include a significantly lower demand case, associated with persistently slow economic growth in the UK, and a high demand case which has a different demand mix to the reference case, driven by high population growth and a strong innovative service-based economy.

An important consequence of the treatment outlined above is that many aspects of energy demand are not endogenously modelled in ESME. Each demand case has a narrative consistent with the levels of population and economic growth specified, but any macro-economic feedbacks between the energy system design and the economy are not modelled. These feedbacks are usually investigated in CGE models or other top-down macro-economic models. Similarly the 'elasticity' of demands, the observed tendency for overall demand level to respond to price, is not modelled in ESME. The tendency, for example, of transport demand to decrease in response to an increase in fuel price (or vice versa), is an observed top-down phenomenon[12]. Demand elasticity can be included in linear optimisation models[15;17] but is not included in the core ESME model. Although this aspect of demand response is not modelled in ESME, 'demand side' technology interventions are included, e.g. insulation retrofits to buildings which, at a cost, reduce the energy required to heat a given building.

The energy services used in the standard version of ESME are listed in Table 3. The choice of energy services reflects some aspects of how different sectors are modelled. For example, in the transport sector separate exogenous demands are required for different modes of travel: car, rail, bus and aviation. One could alternatively define a single demand for one 'passenger transport' energy service and provide cars, trains, buses and aeroplanes as alternative technologies capable of satisfying that one demand. This is not done because modelling the choices between transport modes is itself a very complicated problem, needing to take account of the cost, availability and desirability of the various options to travellers with a range of budgets and in a range of locations. Modelling transport mode choices was therefore determined to be out of scope for ESME early in the development process and this is directly reflected in the choice of energy service demands for the transport sector.

4.4.1 Demand: related decision variables

- No decision variables are directly related to demand.

4.4.2 Demand: related constraints

- Product balances are applied for each energy service product, for each year t, in each region i.

4.5 Resources

Resources are a subset of the products in ESME, being the products which can be sourced from outside the energy system. All other products can only be obtained as the output of a technology. An energy system in ESME can be thought of as a collection of chains:

$$\text{Resources} \rightarrow \text{Technologies} \rightarrow \text{Energy service demands}$$

of which resources are the starting point, as shown on the left hand side of Figure 2. Note that it is possible for a resource product to be produced by a technology within the energy system as well as sourced from outside. Gas in Figure 2 is an example: gas can be sourced from outside the energy system at a cost, shown by the red bar on the extreme left, and gas can also be produced by the anaerobic digestion technology, which consumes the wet waste resource and produces gas, as can be seen by the purple stripe in Figure 2.

Any resource in ESME can optionally have a cost, a carbon content and a limit on the maximum quantity of the resource available. The resources in ESME are divided into two broad categories:

- UK renewable energy resources (e.g. wind, hydro etc.) which are generally limited by physical constraints and cost free.

- Internationally traded fuels (e.g. fossil fuels and nuclear fuel) which are generally unlimited in quantity and have a nonzero resource cost. The resource cost can vary by demand case, so that a narrative of high growth and high demand can be accompanied by high commodity prices.

In most cases the resource limits and carbon contents are straightforwardly based on physical data, though this is not always the case. For example, the core ESME model includes UK domestic biomass, imported biomass and imported biofuel as resources. Both the potential quantity and carbon content of these resources in future decades is uncertain, and will depend on many different factors[5]. The rationale for the data ETI uses in ESME is as follows:

- UK domestic biomass is constrained by a resource limit which is a theoretical estimate of maximum UK production which would be economical and sustainable, and not displacing UK food production. It is assumed that the UK benefits from a CO_2 emissions credit associated with the growth phase of the biomass, and that the credit covers 90% of the carbon content of the biomass, the other 10% being lost to emissions in processing, transportation or farming practices.
- Imported biomass is constrained by a resource limit which reflects estimates of the size of the future global market and the proportion of the market accessible to the UK. It is assumed that the UK buys the CO_2 emissions credit associated with the growth phase of the biomass and that this covers 70% of the carbon content of the biomass, the other 30% being lost to emissions in processing, transportation or farming practices.
- Imported biofuel is constrained by a resource limit which is an estimate of the UK's 'fair share' of global biofuels. It is assumed that the UK buys the CO_2 emissions credit associated with the growth phase of the biomass and that this covers 60% of the carbon content of the fuel, the other 40% being lost to emissions in processing, transportation or farming practices.

In the case of fossil fuels, the carbon content is set to represent the carbon physically contained in the fuel and which will be liberated as CO_2 when the fuel is combusted. This reflects the standard approach that emissions from fossil fuel extraction overseas would not be counted in the UK emissions budget. Of course these numbers can easily be updated in ESME to test the effect of attributing these extra emissions to the UK. Emissions from the fossil fuel extraction which does take place in the UK are tracked separately in ESME along with industrial process and other emissions, not linked directly to the quantity of the resource used in the energy system.

4.5.1 Resources: related decision variables

- A decision variable tracks the quantity of each resource which is sourced in each region i and each year t.

4.5.2 Resources: related constraints

- Energy resource limits apply per region, if limits are supplied by the user.

4.6 Technologies

Technologies are the workhorses of the ESME model, with the definition including any process which converts one or more product into one or more product. This broad definition includes power stations, vehicles, heaters, cookers, buildings & industry sectors, some of which (e.g. power stations) are identifiable devices or plants, whereas others (e.g. industry sectors) are umbrella terms for the aggregate of a number of processes which consume and produce products. Technologies are generally deployed in a buildyear b and retired at the end of their user-specified technical life. In addition it is possible to specify existing technology capacity already deployed at the beginning of the pathway, and it is also possible to permit technologies to be retired before their technical end of life.

Each technology can have any combination of input and output products. The ESME GUI also allows for a change in conversion efficiency (relative to 2010) to be given for future vintages in buildyears $b > 2010$. The deployment of a technology and its operation are conceptually separated, so that once capacity of a technology is deployed it can operate in a number of different modes which may have different combinations of inputs & outputs and different efficiency. A distinction is drawn between technologies as either *fixed* or *flexible*:

- Fixed technologies, once deployed, have a predetermined operation pattern. Solar PV is an example of a fixed technology which has one mode (with solar resource input and electricity output) and having user-specified loadfactors (per region and per timeslice). A dwelling is a fixed technology with ten modes: each mode has inputs of heat & lighting corresponding to demand in a particular timeslice, and user-specified loadfactors in this case are configured to operate the technology in the mode corresponding to each timeslice. In other words the dwelling has inputs of heat & lighting in the 'Winter Morning' timeslice which corresponds to the user-specified inputs appropriate to that timeslice. This in turn drives the seasonal and diurnal variation in demands for heat, light, electricity etc.
- Flexible technologies, in contrast, have separate decision variables for the capacity deployed and the operation of the technology. A coal power station is an example of a flexible technology which has two modes, the first mode having coal input and electricity output, the second mode represents cofiring of biomass and has a combination of coal and biomass inputs with electricity output. Once 1GW, say, of coal power station capacity has been deployed a separate Activity decision variable is available to determine to what extent each mode is operated during each timeslice.

Flexible technologies are important to capture system-level decisions around how certain technologies could be operated differently at different times within a year or at different stages in their technical lives, but they impact on problem size by requiring a larger number of decisions variables. This is partly mitigated by classifying all technologies as either NTS, STS or TS to reflect the maximum timeslicing of the input & output products of the technology. For example an NTS technology only has a decision variable for annual activity: it has NTS inputs & outputs only, and because these products are only balanced annually there is no requirement to resolve the technology activity per season or per timeslice.

The user-specified technology dataset includes assumptions for how parameters such as cost and efficiency of each technology change over the pathway. As discussed in §4.2 this is captured in the model via technology vintages associated with buildyears b. The process of technology learning is not itself modelled in ESME: cost reductions are specified by the user inputs and do not reflect the quantity of deployment selected in the energy system design. For many (but not all) technologies the quantity of deployment in the UK is not material to the global total, hence it is a good approximation to neglect the impact of UK deployment on the technology learning. A consequence of this treatment of learning curves is that the cost and performance data used in ESME should generally reflect 'n^{th} of a kind' (NOAK) technologies rather than 'first of a kind' (FOAK). The additional cost which would in reality be incurred to deploy FOAK technologies first in order to attain the NOAK costs and performances later must be assessed off-model, by inspection of the energy system pathway.

A small subset of the technologies are classified as retrofit technologies and these are treated differently. A retrofit technology is a special type of technology which has the effect of converting one unit of a pre-existing technology (the parent) into one unit of a second technology (the child). Examples include CCS power station retrofit, which converts 1GW of the 'CCGT' technology to 1GW of the 'CCGT with CCS' technology. The retrofit technology has its own capital cost but all other attributes are determined by the parent and child technologies.

4.6.1 Technologies: related decision variables

- Capacity of technologies installed (deployed) per region i and buildyear b.

- Early retirements of technologies per region i, installed in buildyear b retired in year t.
- Capacity of retrofit technologies installed per region i and buildyear b.
- Activity of all flexible technologies per year t, region i, buildyear (vintage) b, mode and timeslice.

4.6.2 Technologies: related constraints

- Pathway deployment constraints which, if data is supplied by the user for a given technology, can limit:
    - Maximum capacity per region .
    - Maximum build rate, via an absolute cap on annual deployment.
    - Maximum build rate, via a cap on percentage annual growth in deployment rate.
- Pathway deployment constraints applying to groups of technologies (e.g. all CCS power stations).
- Security of supply constraints, see §4.9 below.
- Technology 'links': optional constraints which limit the capacity of one technology to be less than the capacity of a second technology multiplied by a user-supplied coefficient. These constraints can be used to limit the number of ground source heat pumps by the number of suitable (i.e. detached) dwellings, or to require that for each electric car there is also an electric charging point.

4.7 Transmission

Transmission is included in the model architecture as a means of moving products from one region to another. In principle any product can be transmitted, although in the current standard version of ESME transmission is only configured for: electricity, hydrogen and captured CO_2. For products such as wind resource, solar resource and end use services transmission makes little sense. For fossil fuels there are existing transmission networks and systems today which could be represented in ESME if desired. They are currently excluded from the model for reasons of simplicity only: future energy systems which meet CO_2 reduction targets will almost certainly require less fossil fuel infrastructure than exists today, and so the costs of maintaining and extending these networks is not likely to be material to the energy system design.

Transmission is much like a flexible technology: capacity deployment is represented by one set of decision variables and transmission flows are represented by another set of decision variables, analogous to technology Activity. For each transmittable product the user must specify: which pairs of regions (i, j) are valid for transmission, a nominal distance between valid pairs of regions and transmission costs & loss factors per pair (i, j). Thus electricity transmission between neighbouring onshore nodes can be differentiated from offshore electricity transmission in terms of cost and loss factor.

With the spatial resolution being at a regional level the representation of transmission in ESME is necessarily coarse. In practice the electricity and gas transmission networks today are clearly much more complex than a series of links between the 12 UK regions. Nevertheless, including transmission in the model does give a means to include some significant extra costs associated with the deployment of some technologies such as offshore renewables. In some cases, e.g. offshore wind, it can be argued that a simple transmission connection from the wind farm to the mainland is a reasonable model of the infrastructure. Whereas for electricity transmission between neighbouring onshore regions the transmission in ESME must represent the aggregate inter-regional transmission of a complicated network, in practice many wires crossing the region boundary with an aggregate capacity determined by '$n - 1$' security criteria.

Distribution

While transmission refers to the movement of products between regions, distribution in ESME refers to the movement of products *within* regions. Given the regional resolution there is no explicit spatial representation of any distribution in ESME, but there are some technologies configured to represent distribution.

For example there is a technology representing electricity distribution, deployment of which represents upgrading the distribution capacity in a given region. The capital cost of this represents a regional average for upgrading the existing distribution network. In the special case of electricity the security of supply constraints are used to determine the distribution capacity required in each region by evaluating the production, consumption and transmission of electricity in the energy system, see §4.9. There are also district heating technologies which represent the deployment of a heat network which distributes heat to dwellings. The capital cost of these represent the average cost per dwelling of installing a heat network in each region.

4.7.1 Transmission: related decision variables

- Capacity of transmission installed (deployed) per region pair (i, j) and buildyear b.
- Flow of product per region pair (i, j), year t, buildyear (vintage) b and timeslice (for TS products).

4.7.2 Transmission: related constraints

- Maximum transmission capacity between node pairs, if data is supplied by the user.
- Onshore and offshore electricity transmission security of supply constraints, see §4.9.

4.8 Storage

Storage in ESME represents within-year storage, i.e. a process that is capable of storing a product from one timeslice to another. Depending on the timeslicing of the product in question, the storage could be either diurnal (i.e. storage of a TS product between two times in a day) or seasonal (i.e. storage of an STS product between seasons).

Storage is much like a flexible technology: capacity deployment is represented by one set of decision variables and the injection/withdrawal processes are represented by another set of decision variables, analogous to technology Activity. Further, for TS products the storage technology deployment is separated into power capacity (i.e. kW maximum energy withdrawal rate) and store volume (i.e. kWh maximum stored energy). For pumped hydro storage these would represent the turbine capacity and the reservoir capacity respectively. The user can specify costs related to these two aspects of deployment, as well as variable costs, loss factors and, optionally, constraints on the ratio of power and volume capacity.

In practice energy storage can operate on a wide variety of timescales, and it is important to note that the representation of storage is strongly dependent on the resolution of the timeslices. The storage in ESME is able to reflect the value of storing energy for one or more timeslices, i.e. a period of several hours, as one strategy for managing imbalances in energy supply and demand over such a timescale. All system dynamics at a shorter timescale, such as frequency management of the electricity system, are not explicitly resolved in ESME. Many short timescale effects are not possible to represent in a model such as ESME, an important point to note when interpreting model results, particularly in a sector such as electricity storage. Some effects on timescales shorter than the ESME timeslices are approximately captured by the security of supply constraints described in §4.9.

4.8.1 Storage: related decision variables

- Power capacity and volume capacity of storage technologies installed (deployed) per region i and buildyear b.
- Injection and withdrawal of stored product per year t, region i, buildyear (vintage) b and timeslice.

4.8.2 Storage: related constraints

- Pathway deployment constraints, if data is supplied by the user.
- Storage technologies can contribute to some security of supply constraints, see §4.9.
- Storage technology 'links': optional constraints which limit the capacity of a storage technology to be less than the capacity of a second technology multiplied by a user-supplied coefficient. For example these constraints can be used to limit the capacity of domestic heat storage per dwelling, to reflect constraints on space availability for hot water tanks.

4.9 Security of Supply

The term security of supply covers a very broad range of issues relating to the reliability of an energy system to meet the demands placed on it. Issues range from the very technical, e.g. '$n-1$' security criteria on the topology of electricity transmission networks, through to the qualitative, e.g. political acceptability of reliance on energy imports. The ESME model includes a number of constraints which aim to enforce technical security requirements, where these are possible to represent or approximate at the resolution of the model. Political aspects of security of supply are by default not modelled in the standard version of ESME, though they can be explored by carefully constructed sensitivity runs.

The spatial and temporal resolution in ESME imply limitations on what can be directly represented in the model, as mentioned in the above sections on timeslicing, transmission and storage. Anything on a spatial scale smaller than a region and anything on a time scale shorter than a timeslice can only be modelled in an approximate fashion, if at all. The flexibility constraint for the electricity system (described below) is a direct example of an attempt to approximate an issue which in reality happens on timescale finer than the timeslices.

Of all the events not fully captured by the timeslices described in §4.2, the most material for the design of the energy system is probably peak demand. The timeslices represent, for example, a typical summer morning, with the intention that they can be aggregated together to form a reasonable approximation to the annual totals for energy consumption and emissions. The peak levels of energy demand seen in a year can be significantly higher than any typical day and, whilst short-lived and hence not significantly affecting annual totals, the energy system must be capable of functioning during the peak conditions. The security of supply constraints in ESME are principally constraints on the installed capacity of technologies, attempting to ensure that sufficient capacity to generate electricity or heat is available to meet peak levels of demand. The peak levels of electricity and heat demand are estimated by extrapolation from the energy demands on a typical day, based on historical data for the ratio between peak and typical demand for various energy vectors: space heating, water heating, lighting, cooking, electrical appliance usage, transport. This extrapolation gives an estimate for peak electricity and heat demands which is used in the constraints described below. In addition to this methodology, the ESME model can also be run in a detailed mode in which the 'peak day' is explicitly represented by an additional 5 timeslices. This gives a more accurate estimate of peak demand levels than the simpler extrapolation method, and also gives more degrees of freedom in terms of how the energy system is operated in peak conditions, but it is considerably more computationally demanding (see §4.11). It is generally used to check the validity of the approximations in the standard model and to calibrate the model if required.

4.9.1 Security of Supply: related decision variables

- A small number of decision variables are used to allocate the renewables electricity capacity into tranches of declining capacity credit for use in the constraint below. No other decision variables are directly related to security of supply.

4.9.2 Security of Supply: related constraints

- Electricity peak reserve. This constraint requires that the total capacity of electricity generating technologies (with capacity credit percentage adjustments for their contribution to peak capacity) exceeds the estimated peak electricity demand by a user-defined reserve margin. The contributions to peak capacity include:
  - Renewables generation such as wind, which is split into tranches of declining capacity credit.
  - Other electricity generation capacity, adjusted by a capacity credit for each.
  - Storage capacity, adjusted by a capacity credit for each.
- Nodal electricity peak reserve. This is similar to the above, but ensures that there is sufficient electricity generation capacity (adjusted for their contribution to peak capacity) or electricity transmission capacity to meet peak demand in each onshore region i.
- Electricity flexibility reserve. This constraint ensures that there is sufficient flexibility from the electricity generation capacity at a system level to meet estimated rates of change in electricity demand. The contributions to flexibility are a simple proxy for the ability of generation plant either to contribute to meeting fluctuating demand within a timeslice (associated with a positive contribution for dispatchable plant), or to place demands for flexibility on the system (associated with a negative contribution for intermittent plant).
- A Multi day no-wind constraint requires that the electricity generation capacity could meet demand during a prolonged period of very low wind.
- Nodal heat peak reserve. This constraint ensures that there is enough capacity to supply peak demand for space heating and water heating.
- Onshore electricity transmission security. A constraint for each onshore region requiring that, if all renewables in the region and connected offshore regions are generating at 100%, then there is sufficient capacity to transmit surplus electricity to neighbouring onshore regions.
- Offshore electricity transmission security. A constraint requiring that the transmission capacity from an offshore region to an onshore region must be greater than or equal to the nameplate capacity of all the offshore renewables.
- Minimum load factor constraints, which allow the user to specify a minimum loadfactor for the operation of any flexible technology per year t and per timeslice. This is used to enforce some operation of 'backup' electricity capacity, which is generally installed to meet the peak reserve constraint. The minimum loadfactors are exogenous assumptions, calibrated by an electricity dispatch model.

4.10 Domestic Heating

In many ways the representation of heating in ESME follows the standard structure described in the above sections, but there are some additional complications. The ESME model is currently configured with 24 categories of domestic dwellings, divided into 3 levels of 'density':

- Flats & apartments

- Semi-detached and terraced homes
- Detached homes & bungalows

and 8 levels of thermal efficiency. As described in §4.6 each dwelling is a fixed technology with inputs of heat and light which vary by timeslice. This configuration of the technologies means that there are choices of dwellings to deploy to satisfy increasing housing demand, with a trade-off between higher cost and higher thermal efficiency. There are also options for insulation, modelled as retrofit technologies which promote an existing dwelling to a higher thermal efficiency category.

Regional variations in numbers and types of dwelling are prescribed via the exogenous energy service demands. However, another important consideration is the regional variation in external temperature and hence in the heating required per house to achieve a desired internal temperature. In order to reflect this the heating inputs to the dwelling technologies are treated differently to all other technologies, and the user is able to specify the inputs differently for different regions. The information to populate these data is generated by an off-model spreadsheet calculation which calculates the heating required per hour based on user-specified data including: dwelling thermal efficiency rating, desired internal temperature, external temperature and the hourly heating pattern. The standard ESME data is configured to reflect a gradual increase in the desired internal temperature for dwellings, increasing to 21.5°C, as well as a small increase in external temperature owing to climate change.

Another important aspect of the heating demand is that, in all cases except for district heating networks (DHNs), the heat is generated within each building from another energy vector. Thus the standard approach described in §4.3 to balance the supply and demand of each product in each region is not sufficient in the case of space heat: it would not guarantee that enough space heat is generated in each individual building. For products such as electricity the standard approach is conceptually appropriate, as multiple technologies supply electricity into a network to be consumed by multiple consumers for whom it is irrelevant where the electricity came from initially. In order to overcome this difficulty for space heat the standard version of ESME contains a number of additional constraints including technology links and a heat link constraint which together try to ensure that any inappropriate supply & demand balances are minimised. These constraints are carefully configured to limit the allowed capacity of heaters, such as ground source heat pumps, by the number of suitable dwellings. For example, ground source heat pumps are configured to be permitted only for a few categories of detached dwellings. The various link constraints ensure that the capacity of ground source heat pumps and the heat they supply cannot exceed the demand arising from the permitted dwellings.

The additional constraints on heater technologies generally perform satisfactorily, but they cannot resolve the problem completely. For this reason ESME also includes an optional ‘buildings association’ (BA) running mode. When run in BA mode, the heat supply & demand balances are segregated for each category of dwelling in each region, and hence there is no possibility for blurring between the heat demand in one building and the heat supply in another building. In order to achieve this each heat balance constraint in the standard model is replaced by 24 in the BA model, and likewise the number of decision variables for the capacity of each heater type (in each region) is multiplied by 24 in order to segregate the capacity in each category of dwelling. The ESME code is capable of reformulating the optimisation in this manner in an automated way, and the BA mode is used to validate that the representation of the heating system in the standard model is satisfactory, and if necessary to calibrate the link constraints applied in the standard model. The BA optimisation is however significantly more computationally demanding, making it too slow to be adopted as the standard approach.

4.11 Optimisation Approach

4.11.1 Objective function

The objective function of the optimisation is system cost, i.e. the optimisation selects the values of all decision variables such that the energy system cost is minimised. The calculation of the system cost comprises two elements: the annualised energy system cost for each year t included in the optimisation and the combination of these annual costs into a single (NPV) cost for the whole pathway.

The annualised system cost for a single year t is defined as the sum of:

- Annualised capital costs for all technologies.
- Operating & maintenance costs of all technologies. These include both fixed and variable costs, but exclude fuel costs.
- Resource costs for all resources sourced from outside the energy system.

Annualised capital costs are calculated using a 10% nominal benchmark discount rate. This reflects a weighted average cost of capital and, assuming an inflation rate of 2%, it corresponds to a real discount rate of 8%. A commercial discount rate is used under the assumption that the energy system will be developed with private investment. Technologies also have a parameter giving the length of any construction period, which is used to estimate the costs of interest during construction.

The total system cost for a whole pathway is defined as the net present value of all the annualised costs for each year t. Calculation of the net present value involves a second discount rate which reflects a societal judgment on the impact of costs now versus costs in the future, sometimes referred to as the Social Time Preference Rate. A value of 3.5% is used in ESME.

All resource and technology costs used in ESME exclude taxes, subsidies and incentives resulting from government policy. In such a long term optimisation model the aim is consider a very wide range of future energy systems, some of which are radically different to today, and hence it is desirable to avoid trying to predict future policies. Instead, the long term optimisation intends to highlight blueprints for energy systems that can be used to inform policy development. Therefore, all the costs exclude taxes and subsidies, and likewise the projections of energy service demand assume a 'neutral' impact of government policy on demand.

4.11.2 Linearity and solution time

The optimisation problem is formulated as a linear program (LP) optimisation. This is considered appropriate for a high-level representation of the energy system, and has the benefits that efficient solution times are possible for large problems as well as having fully reproducible results. A fast solution time is important partly to make ESME a responsive tool which can be used to perform test runs, and is also critical to the use of ESME as a Monte Carlo model. It is designed that a single optimisation can be performed in less than five minutes, allowing a Monte Carlo run to be performed overnight.

A more detailed approach would be to represent technologies, e.g. large power plants, via discrete decisions, which would require a more complex and computationally intensive mixed integer program. Given the very high-level overview of the energy system represented in ESME, this is not necessary. Nevertheless, formulating the problem as an LP does introduce approximations, and it limits the types of constraints and cost functions that can be used to those which are linear in the decision variables.

A typical optimisation in ESME with decade time steps can have over $100,000$ decision variables and a similar number of constraints. Increasing problem size leads to increased computer memory requirements, reduced numerical stability and longer solution times. LP optimisation can be shown to be possible in polynomial time (i.e. polynomial in the number of decision variables), and using modern computational algorithms a quadratic or cubic scaling can often be achieved. The single biggest contributors to the number of decision variables are the Activity variables for the flexible TS technologies. The number of these variables scales with:

- The number of flexible TS technologies.
- The number of regions i.
- The number of buildyears b.

- The number of timeslices.
- The number of optimised years t.

Thus maintaining a tractable optimisation requires a fine balance to be maintained between the model resolution in terms of technologies, time and space.

Using functionality incorporated into the Aimms optimisation software, all the data and variables in the ESME model have assigned units of measurement (e.g. kW, kWh, etc.). These provide a useful check on the code that all quantities are being manipulated and combined in a dimensionally consistent way, and they also give a means to adjust the scaling of the LP. For example the optimisation can be formulated with the decision variable for the deployed capacity of nuclear power stations in units of kW, MW, GW or indeed any other unit of power. Choosing units which are appropriate to the problem results in a better scaled problem (i.e. a matrix with a lower condition number κ) to be passed to the solver algorithm, which in turn has a significant effect on the solution time and numerical stability.

4.11.3 Monte Carlo uncertainty analysis

ESME is used as a Monte Carlo model to reflect uncertainty in the future value of key parameters. In principle virtually all of the data inputs can be modelled as uncertain, however in practice this is usually restricted to energy resource costs, energy resource quantities and technology costs. To reflect the uncertainty in future technology costs, for example, the user can define ranges and probability distributions for the future values of these parameters. The user can also, optionally, specify correlations between any of the uncertain parameters (e.g. costs of gas CCS and coal CCS power stations). As described in §2.3, the Monte-Carlo functionality effectively enables an automated way to perform large volumes of sensitivity analysis.

The results of a Monte Carlo run are a set of perhaps 100 or 1000 energy system designs, each corresponding to the least-cost energy system in a different eventuality. The combined results can be used to assess the technology capacity levels seen under different eventualities of the assumed uncertainties, and can be visualised via histograms, scatter plots or box & whisker charts. Going further, there are many derived quantities which can be similarly viewed, e.g. the average electricity grid carbon intensity, or the rate of carbon abatement in the different sectors.

It's important to note that for each individual case in a Monte Carlo run, the optimisation is performed with knowledge of the costs and prices in all years, so effectively benefitting from perfect foresight. Nevertheless, when used as part of a broader sensitivity analysis, the Monte Carlo functionality can clearly give some insights into the trade-offs which apply to the transition pathway of the energy system. This can then suggest strategies for managing risk and timing of decisions, but this must be inferred off-model. Alternative treatments of uncertainty are required to incorporate such questions directly into a model. For example, a stochastic programming treatment of the future uncertainties, in which the goal of the optimisation is find a deployment strategy which minimises the *expected* total system cost given the prescribed uncertainties. Such an approach has been applied to similar models[14], although it is only possible to include a very limited number of uncertainties because the size of the resulting optimisation grows exponentially.

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